

# Experimental-calculated study of the forced convection magnetic nanofluids

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**Abstract.** Experimental-calculated study of the magnetic nanofluids forced convection in a constant magnetic field was carried out. Dependence study of the magnetic nanofluid heat transfer coefficient on the effect of a constant magnetic field was made. For numerical simulation we have used Euler-Lagrange two-component approach.

## 1. Introduction

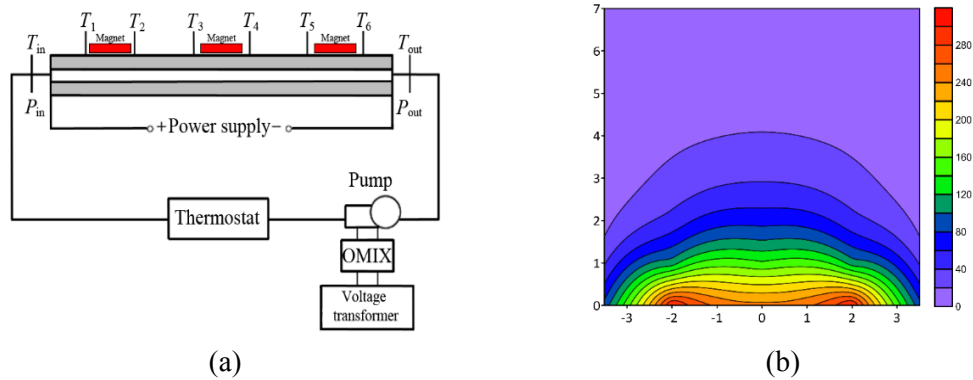
One of the solutions to the problem of heat transfer performance enhancement could be the use of so called nanofluids, which are fluids containing nanoparticles of various composition. The use of electromagnetic fields is a promising way to control the properties of nanofluids. The magnetic field can be influenced by nanofluids prepared from ferromagnetic materials (ferromagnetic nanofluids), for example, from iron nanoparticles, its oxide ( $\text{Fe}_3\text{O}_4$ ), nickel etc. Such fluids can be extremely useful in many applications.

Articles [1-3] investigated the nanoparticles transport in the channels with influence of the magnetic field. Sundar et al. [1] studied turbulent forced convection heat transfer and friction factor of  $\text{Fe}_3\text{O}_4$  magnetic nanofluid in a tube in the absence of magnetic field and developed correlations for the estimation of Nusselt number and friction factor. Their results show that the heat transfer coefficient is enhanced by 30.96 % and friction factor by 10.01 % at 0.6 % volume fraction compared to the base fluid. Recently, Ghofrani et al. [2] investigated the effect of constant and alternating magnetic fields on the forced convection heat transfer in a short tube. They showed that increasing the alternating magnetic field frequency increases the heat transfer up to of 27.6 % in low Reynolds numbers. Lajvardi, et al.[3] experimentally studied the convective heat transfer of water –  $\text{Fe}_3\text{O}_4$  ferrofluid flowing through a tube in laminar regime in the presence of magnetic field perpendicular to the flow direction. Experiments were carried out on ferromagnetic fluids at different concentrations and in different configurations of the magnetic field. They concluded that by improving the thermophysical properties of the ferrofluids, heat transfer can be attributed in the presence of magnetic field.

Thus, despite the existing experimental data, they are quite contradictory and do not allow comprehending clearly the mechanisms of heat transfer magnetic nanofluids. This circumstance requires additional systematic study of forced convection of magnetic nanofluids.

## 2. Description of the experimental setup

Experimental study of the forced convection of magnetic nanofluids in a constant magnetic field was carried out. The experimental unit is a loop with a circulation coolant. The experimental unit diagram is shown in Figure 1(a).



**Figure 1.** The experimental unit diagram (a); The magnetic field induction over the magnet (mT) (b).

The working fluid is pumped to the heated test section from the accumulator tank. The gear pump WT30001 was used for pumping a nanofluid. Pump drives provide the ability to pump different fluids at a flow rate from 85.7 to 2571.4 ml/min.

After passing the heated section, the liquid enters the heat exchanger and gives heat to the thermostat. The working fluid flow rate in the circuit is regulated by control valves. Monitoring of the flow rate in the circuit is carried out by flowmeter. The heated section is a stainless steel tube with a diameter 10 mm and a length of 1 m. The wall thickness is 1 mm. Electric current is supplied to the wall for heating. This ensures the conditions of constant heat flow on the wall. Heating power is regulated by LATR. 6 copper–constantan thermocouples are fixed on the wall at an equal distance from each other to measure the local temperature of the tube. The temperature is read by the TPM-200 meters. The temperature at the inlet and outlet of the heated section is measured by thermocouples. In this case, the thermocouple for measuring the ambient temperature at the circuit outlet is located at a considerable distance from the heated section end to ensure ambient temperature uniformity at the measurement site. The circuit section from the heater to the ambient temperature measurement site was heat insulated. The drop pressure study at the inlet and outlet of the heated section was also measured. The pressure drop over the length of the working section is measured by a differential pressure gauge OWEN PD200. The experimental unit for measuring heat transfer coefficient was tested using the known empirical data for the heat transfer of pure water.

Three permanent neodymium magnets with dimensions 50x30x10mm were used to create a magnetic field. The magnetic field intensity around the magnet was measured with a milliteslameter TPU-02. The distribution of the magnetic field induction over the magnet is shown in Figure 1(b). The maximum value of the magnetic induction near the magnet is of the order of 0.3T. In experiments, the magnets were located in the immediate vicinity of the heated section at the same distance from each other.

A round glass channel with a diameter of 10 mm and a length of 1 m was used to visualize the flow of a magnetic nanofluid. It was installed in the experimental unit instead of the measuring section.

Iron oxide nanoparticles  $\text{Fe}_3\text{O}_4$  were used to prepare the nanofluid. The average particle size was 100 nm. Distilled water was used as a base fluid. The volume density of nanoparticles was 0.75%. A standard two-step method was used to prepare the nanofluid. Suspensions were processed in an ultrasonic bath "Sapphire TC-10338". The nanofluids were free of surfactants.

The nanofluid viscosity was measured at a Brookfield DV2T rotary viscometer with a low viscosity ULA adapter (0). The measurement accuracy for the viscosity coefficient was not less than 2.5%. The viscometer was calibrated with distilled water and ethylene glycol before the measurements.

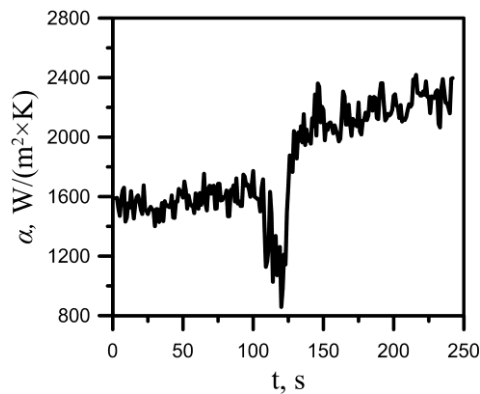
The coefficient of thermal conductivity of nanofluids was measured using a non-stationary hot wire method. The detailed description of the installation and its testing is given in [4].

### 3. Experimental results

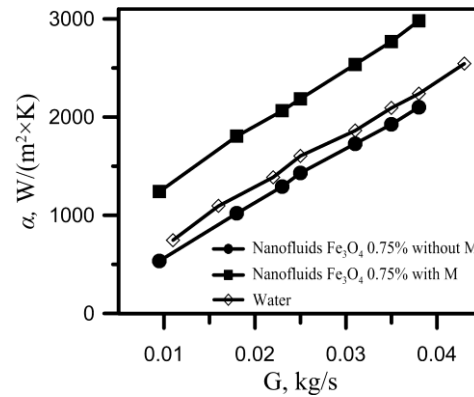
The average and local values of the heat transfer coefficient at the channel walls were measured as a result of experiments. A strong influence of a constant magnetic field on the forced convection of the magnetic nanofluid was shown during the experiments.

The graph of the average heat-transfer coefficient versus time (Figure 2) shows that the heat transfer coefficient increases with the constant magnetic field action. Measurements were made without the magnetic field action in the interval from 0 to 100 s. After that, three permanent magnets were installed near the working section wall, and the recording of the measured parameters was not interrupted. The average heat transfer coefficient was shown to increase.

The magnetic field action on the nanofluid heat transfer coefficient with a nanoparticle volume density of 0.75% was investigated. The influence of the magnetic field intensifies the average heat transfer coefficient by 55% relative to the base fluid at a fixed flow rate, while the nanofluid heat transfer coefficient without the magnetic field influence is 10% below pure water. The dependence of the heat transfer coefficient on the flow rate is shown in Figure 3.



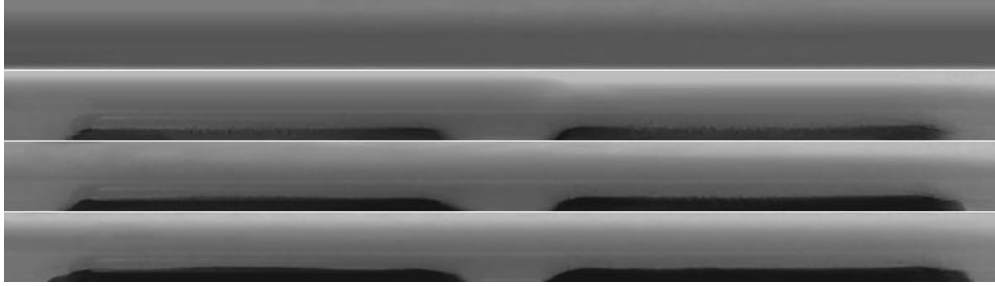
**Figure 2.** Dependence of the average heat transfer coefficient on time ( $\text{Fe}_3\text{O}_4$  100nm, 0.25%,  $\text{Re}=1400$ ).



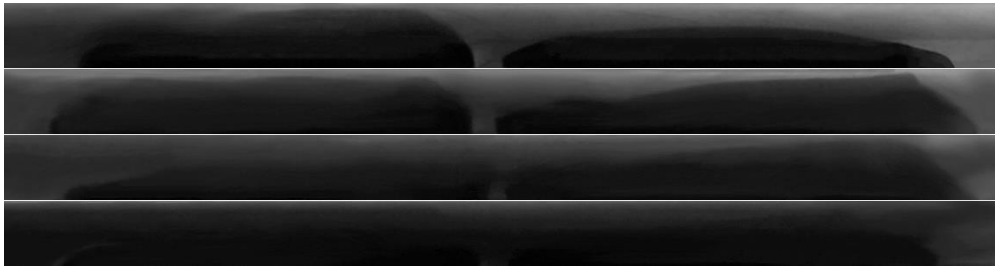
**Figure 3.** Dependence of the average heat transfer coefficient on flow rate with and without the magnetic field action ( $\text{Fe}_3\text{O}_4$  100nm, 0.75%).

The flow structure was visualized under the action of a magnetic field. The least particle concentration of 0.01% was used for better visibility. Figure 4 shows photographs of the deposits formation on the channel wall from the time at the Reynolds number of 1750. Analysis of the deposits formation dynamic shows that the deposits shape continues to change for about 100 s. After this a dynamic balance is established between deposition and particles entrainment, and the deposits shape stabilizes. Figure 5 presents experimental photographs of nanoparticle deposits on the channel wall a minute after the deposits beginning. The volume concentration of the nanoparticles was 0.125%, the Reynolds number varied from 2000 to 5000.

Visualization shows that the nanoparticle deposits significantly distort the flow pattern in the channel. The fluid must flow around deposits, as a result, there is a local velocity increase in the gap between the channel wall and deposits. In addition, flow recirculation zones behind deposits from nanoparticles are well visible. For large values of the Reynolds numbers, the flow in the flow around the deposits becomes nonstationary and accompanied by an intense vortex separation and significant flow fluctuations.



**Figure 4.** The deposits form on the tube wall at different times for  $Re = 1750$ . Top-down: 0s, 5s, 20s, 60s. The nanoparticles concentration in water is 0.01%, the magnetic field induction is 325 mT.

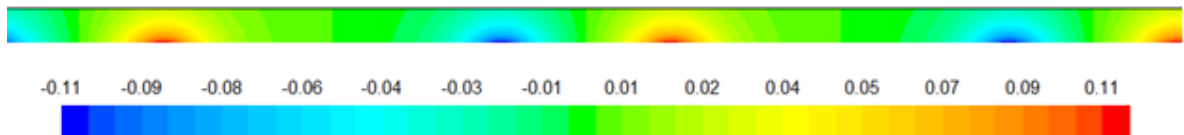


**Figure 5.** The deposits form on the tube wall a minute after the start of the deposition process. Top-down:  $Re = 2000$ ,  $Re = 3000$ ,  $Re = 4000$ ,  $Re = 5000$ . The nanoparticles concentration in water is 0.125%, the magnetic field induction is 325 mT.

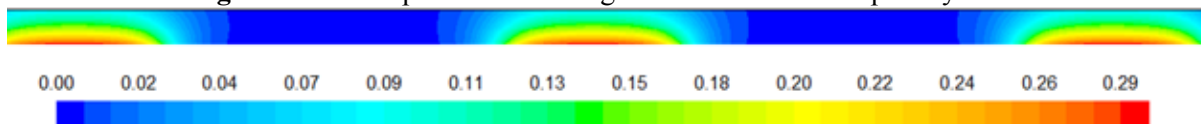
#### 4. Numerical simulation

To simulate the transport of nanoparticles in the magnetic field we used a Euler-Lagrange combined two-component approach. As part of the Lagrange approach for the base fluid the equations of continuity, momentum and energy were being solved, and the movement of the particles was modeled on the basis of Newton's second law by solving an ODE. Euler two-component model describes nanoparticles in a liquid as a binary mixture, one of which components is nanoparticles. Statement of the problem completely repeated the experimental study. The computational domain is a circular channel with an inner diameter of 10 mm and a length of 1 m. A computational grid consisting of 850 thousand nodes, was used for the simulation.

Figures 6-7 show the distribution of the magnetic induction components in the channel and the distribution of the magnetic force in the channel, when the magnets are as close as possible to the channel wall.

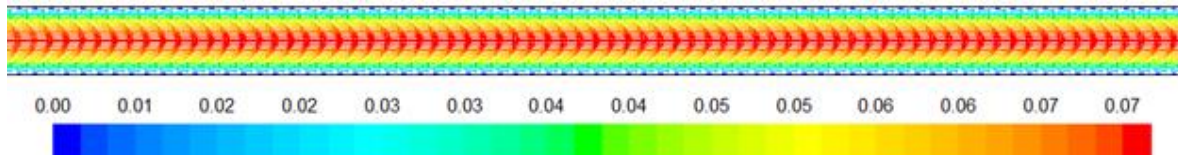


**Figure 6.**  $B_x$  component of the magnetic induction in the plane  $y = 0$ .

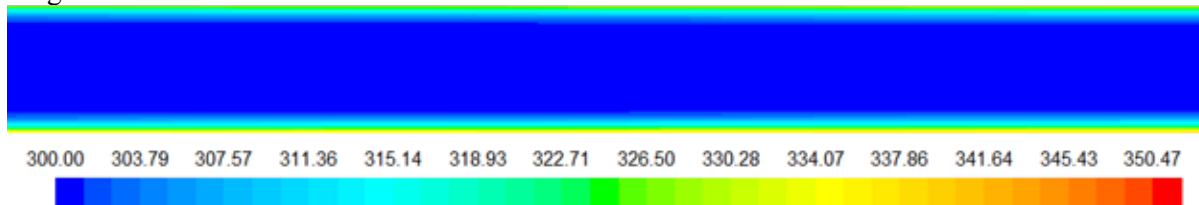


**Figure 7.**  $B_z$  component of the magnetic induction in the plane  $y = 0$ .

Figures 8,9 show the vector velocity field in the channel and the temperature field without a magnetic field. There is no the nanoparticles deposition on the channel surface.

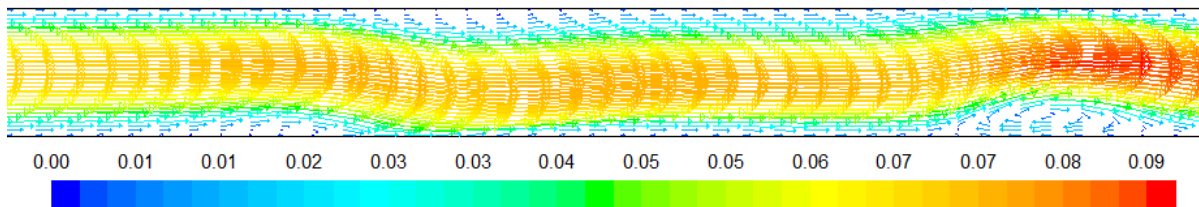


**Figure 8.** The vector velocity field in the channel for the Reynolds number of 1500 without a magnetic field.

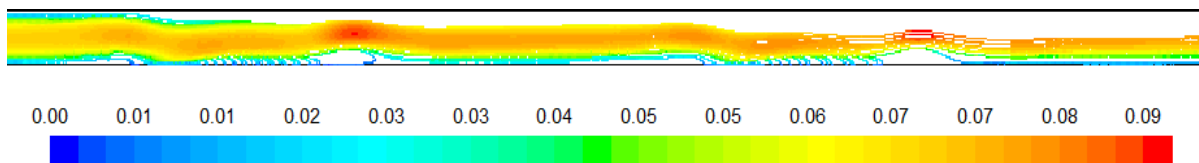


**Figure 9.** The temperature field in the channel for the Reynolds number of 1500 without a magnetic field.

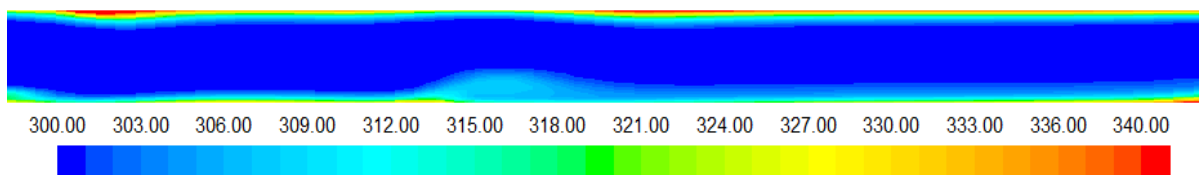
A series of calculations of heat transfer in a magnetic field was carried out. Figures 10-12 show the results of calculations for the Reynolds number 1500. Powerful deposits of particles are formed on the channel wall. The nanoparticles path for this variant are shown in Figure 11. In addition, the interaction of the magnetic field with the particle flow leads to the formation of recirculation zones. It was found that the nanoparticle deposits formed in the channel significantly distort the velocity profile of the flow. The fluid must flow around deposits, as a result, there is a local velocity increase in the gap between the channel wall and deposits.



**Figure 10.** The vector velocity field in the channel for the Reynolds number of 1500 with a magnetic field.



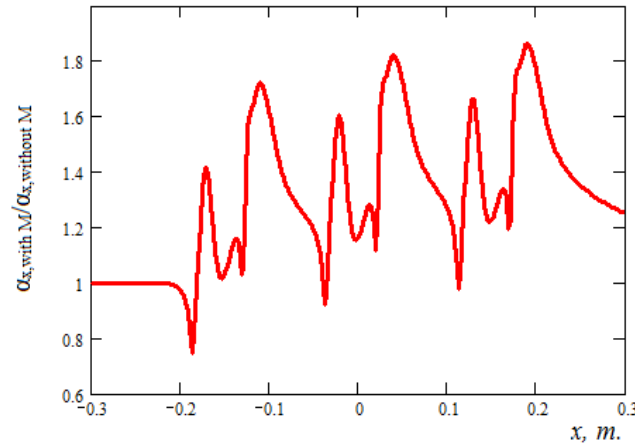
**Figure 11.** The nanoparticles path for the Reynolds number of 1500 with a magnetic field.



**Figure 12.** The temperature field in the channel for the Reynolds number of 1500 with a magnetic field.

Figure 13 shows the calculated distribution of the increment of the local heat transfer coefficient at the tube wall for Reynolds number of 1500 with a magnetic field. The recirculation zones of the flow

and local inhomogeneities of the velocity field in the scope of the magnetic field lead to a significant increase in the local heat transfer coefficient.



**Figure 13.** Exceeding the local heat transfer coefficient under the action of the magnetic field for  $Re = 1500$ .

## 5. Conclusions

As a result of the experiments, the mean and local values of the heat transfer coefficient at the channel walls were measured. The dependences of the heat transfer coefficient and the flow rate of the nanofluid are obtained. The experiment established that the local heat transfer coefficient of the magnetic nanofluid increases with influence of a constant magnetic field. At the locations of the magnets, the local heat transfer coefficient increases to 1.8 times relative to the nanofluid without the influence of the magnetic field. It is shown that the average heat transfer coefficient of magnetic nanofluids with iron oxide nanoparticles  $Fe_3O_4$  is increased by up to 1.55 times in comparison with the base fluid by means of a stationary magnetic field. It was shown that the interaction of the magnetic field with the particle flow leads to the deposits formation of nanoparticles on the tube walls at the locations of the magnets by numerical simulation. These deposits lead to a significant distortion of the local flow structure in the channel and to the formation of flow separation. It is the main reason for increasing the heat transfer coefficient.

## Acknowledgments

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